SOME ASPECTS OF THE DEVELOPMENT OF HURRICANE DOROTHY

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ABSTRACT

Hurricane Dorothy, July 1966, possessed both extratropical and tropical features. A number of factors contributed to storm development, including a well-defined pre-existing disturbance, high-level advection of vorticity and kinetic energy, baroclinicity of both the extratropical and tropical-storm types, and a moderate degree of latent instability.

1. INTRODUCTION AND SUMMARY

Dorothy, the fourth storm of the 1966 season, developed in the central North Atlantic, near 32° N., 42° W., on July 22–23 [1]. The storm attained winds of 50 kt. on July 23 and hurricane-force winds of 65 kt. late on July 24. The area of formation (north of 30° N. and in the general environment of an upper-tropospheric cold Low), the seeming absence of a well-developed wall cloud and warm core on July 23–24, and the unusual appearance of the storm in the satellite photographs suggested to forecasters that Dorothy may not have been a true tropical storm during that time.

Dorothy did indeed possess some extratropical features. One purpose of this paper is to present evidence of that. A second purpose is to evaluate, where possible, some of the factors contributing to the cyclogenesis. Just prior to storm formation, the initially weak disturbance received a rather strong influx of kinetic energy and cyclonic vorticity at upper-tropospheric levels. This was associated with a vigorous short-wave trough advancing toward the area from the north and northwest. Storm development occurred as the high-level perturbation approached and moved over the lower-level disturbance. At Weather Ship "E", located some 400 mi. to the northwest of the storm center, pronounced mid-tropospheric cooling, stratospheric warming, and a lowering of the tropopause occurred during and after the day of storm formation. The temperature changes at ship "E" strongly suggest some influx of baroclinicity into the area, although no low-level frontal zone can be defined.

These events indicate that Dorothy very probably derived a considerable portion of its energy from extratropical sources during the period July 22–23, although convective instability and the release of latent heat undoubtedly contributed to development. In this sense, Dorothy was, at best, a "half breed". [1] Later, during July 25–28, there is some evidence to indicate that Dorothy did develop a weak warm core and was more nearly a true tropical cyclone.

This paper is confined largely to the developmental period, July 22–23. The more general history of Dorothy, the storm track, and discussions of other 1966 Atlantic storms are given by Sugg and Staff [1] elsewhere in this issue.

2. SYNOPTIC SITUATION AT 0000 GMT, JULY 22

Figure 1 shows the surface charts for 0000 GMT and 1200 GMT on July 22 and 23. Figures 2a–d give the 300-mb. analyses for the same hours. On both sets of charts all available data are plotted within the region 20°–60° W. and 20°–45° N. At 300 mb. some surrounding data also are shown, and the analyses are extended to include a somewhat larger area.

The general situation aloft over the North Atlantic at 0000 GMT, July 22, featured a large blocking High centered well north of 45° N. South and east of the High was a complex upper-tropospheric cold Low. At 300 mb. (fig. 2a), the main center of the Low was located near the Azores, but there were several rather well-defined perturbations revolving about the main center and extending many hundreds of miles outward. As seen in the subsequent charts (figs. 2 b, c, d), one of these perturbations—the upper-level trough extending far to the northwest of the low center at 0000 GMT—later advanced southward and passed over the disturbed area, accompanied and preceded by a pattern of considerable cyclonic vorticity advection. This is believed to have been a significant factor in the development of Dorothy. However, at 0000 GMT, July 22, that upper-level perturbation was still quite far from the disturbed area. The disturbance lay under a weak trough, almost midway between the large Azores Low and an anticyclone centered northeast of Bermuda.

At the surface at 0000 GMT, July 22 (fig. 1a), can be seen the well-defined but weak disturbance in the shape of an inverted trough embedded in the southern sector of the

[1] This term was used by Dunn and Staff [2] and Frank [3] to describe a similar Atlantic storm that occurred in 1963. They indicate that several such "half breeds" may occur each year.

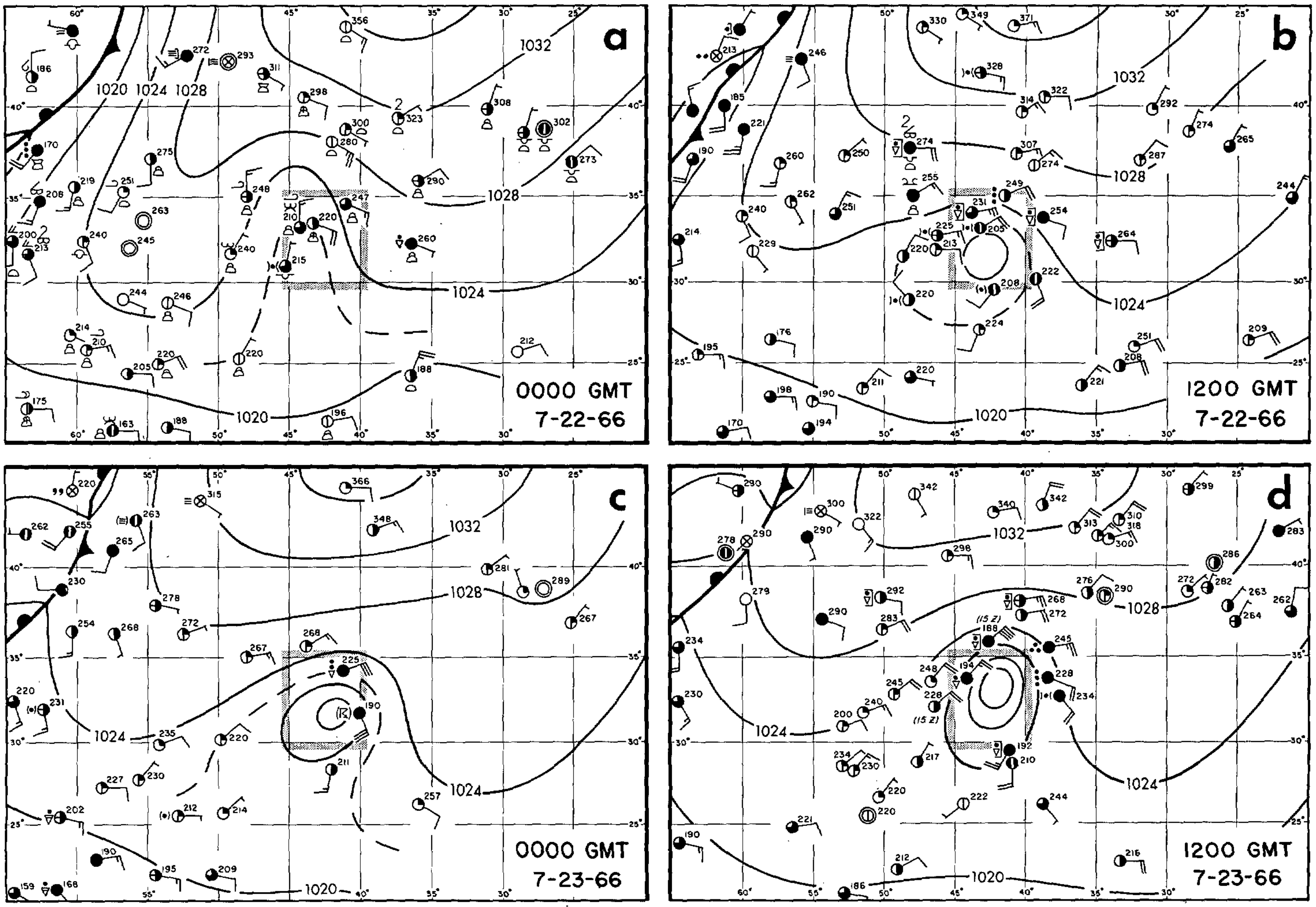

FIGURE 1.—Surface synoptic analyses in vicinity of developing storm Dorothy for (a) 0000 GMT, July 22; (b) 1200 GMT, July 22; (c) 0000 GMT, July 23; (d) 1200 GMT, July 23, 1966. All available ship reports are plotted. In most cases only sea level pressure, wind, sky cover, and present weather are shown.

large High. Forecasters had been aware of its existence for several days. However, at 0000 GMT, July 22, no closed isobar could be drawn, and it is remarkable that the lowest pressure in the area of subsequent storm formation was above 1020 mb.! An ESSA–1 cloud photograph taken some 8 hr. earlier (fig. 3a) reveals a bright cloud mass with geometric center near 32° N., 39° W.—slightly east of the surface trough. A very faint and small-scale spiral array of cloud lines is centered near 31.5° N., 43.5° W.—west of the main cloud mass and in good positional agreement with the nearly stationary inverted trough. That small-scale spiral array appears to be composed of low or middle clouds and is interpreted as indicating cyclonic vorticity at lower-tropospheric levels but not necessarily a closed cyclonic circulation. The latter, if it existed, must have been small and weak.

3. STORM DEVELOPMENT ON JULY 22–23

By 1200 GMT, July 22, a small surface low center had formed (fig. 1b), but the lowest pressure was still near 1020 mb. At 300 mb. for the same time (fig. 2b), the upper-level trough to the north had advanced somewhat southward from its previous position at 0000 GMT, as evidenced by the pronounced shift in the wind at Weather Ship "D" (44° N., 41° W.) from 030° to 100°. Some intensification of the trough appeared likely. At Weather Ship "E" (35° N., 48° W.), located south of the approaching trough and northwest of the low-level disturbance, increased winds from the north-northwest and north had begun to appear in the 300–200-mb. layer (see also time section, fig. 5). An ESSA–1 photograph taken 3 hr. later (fig. 3b) shows the bright cloud mass of the disturbance centered near 32.5° N., 40° W.—again slightly east of the surface Low. No well-defined bands are visible, but the cloud mass appears to be more compact than it was on the previous day, and some cirrus outflow is seen in the northeast fringes.

Storm formation occurred July 23 [1]. Surface ship data are not adequate to define the period of most rapid deepening, but it probably occurred sometime between

0000 GMT and 1500 GMT, July 23. Winds up to 30, 40, and 50 kt. were reported at 0000 GMT, 1200 GMT, and 1500 GMT, respectively (see surface maps, figs. 1c, d). The storm was named Dorothy later the same day. The concurrent 300-mb. charts for 0000 GMT and 1200 GMT (figs. 2c, d) show that the advancing upper-level trough continued to move toward the storm area, forming a small low center as it dropped southward. A strongly difluent flow pattern developed in advance of the oncoming trough and over the area of the deepening storm.

Figure 4 presents a striking series of photographs taken over a period of about 4½ hr. during the July 23 deepening. No eye is visible. Instead one sees the progressive development of a tightly wound spiral configuration in which both the major cloud band and the relatively cloud-free zone spiral inward to the center in much the same fashion as in many extratropical cyclones!

4. FACTORS CONTRIBUTING TO CYCLOGENESIS

The approach of a vigorous upper-tropospheric trough toward the area of a pre-existing low-level disturbance is known to favor subsequent cyclogenesis through the mechanism of high-level vorticity advection (Petterssen [4]). Neglecting small terms, the vorticity equation may be written

$$\frac{\partial Q}{\partial t}+V\frac{\partial Q}{\partial s}=(V-C)\frac{\partial Q}{\partial s}=-QD \qquad (1)$$

where Q is the absolute vorticity, D is the horizontal divergence, s is the direction along the streamlines, V is the wind speed, and C is the phase speed of the system (trough speed). If upper-level winds are blowing through the trough with great speed ($V>>C$), the area immediately in advance of the trough may see the vorticity advection term, $V\partial Q/\partial s$, become a large negative quantity relative to $\partial Q/\partial t$. Positive upper-level divergence may be accompanied by semicompensating low-level convergence in such areas.

That such a mechanism was operating to some degree in this case seems extremely likely. The author offers the hypothesis that it was a vital contributing factor in the development of this storm. Although the terms of equation (1) cannot be evaluated with any precision, it is obvious from the analyses presented in figures 2c and d and the strong upper winds shown in figure 5 that upper-level vorticity advection was large over and immediately upstream from the area of low-level cyclogenesis. At a point near Weather Ship "E" (35° N., 48° W.) at 0000 GMT, July 23, in the upper troposphere, some reasonable but very crude estimates of the quantities of equation (1) might be:

$$V=40 \text{ m./sec.},$$
$$C=10° \text{ lat. per 24 hr.} \approx 13 \text{ m./sec.},$$
$$\partial Q/\partial s=-10^{-4} \text{ sec.}^{-1} \text{ per 600 km.},$$
$$Q=2 \times 10^{-4} \text{ sec.}^{-1}$$

TABLE 1.—*Computed estimates of mean horizontal divergence, $\overline{D}$, and mean relative vorticity, $\overline{\zeta}$, for the 5-degree "square", 30°–35° N., 40°–45° W., at sea level. Units are 10^{-5} sec.$^{-1}$*

	July 22–1200 GMT	July 23–1200 GMT
$\overline{D}$	−1.1	−3.0
$\overline{\zeta}$	4.1	8.3

Insertion of these quantities into equation (1) yields a value of $D\approx 2.3\times 10^{-5}$ sec.$^{-1}$ Although the accuracy of this computation must be considered very low, it seems fair to say that D was certainly positive in sign over that area, and probably was relatively large. Petterssen [4] quotes values of D of 0.8×10^{-5} sec.$^{-1}$ and 3.2×10^{-5} sec.$^{-1}$ as representative of moderate and intense synoptic-scale systems, respectively.

Several years ago Namias [5] stressed the importance of injection of cyclonic vorticity from troughs in the westerlies into the Tropics for providing a favorable "climate" for tropical storm formation. The present case, although it occurred somewhat north of the Tropics, seems a good illustration.

Table 1 shows the results of two kinematic computations of mean divergence and mean relative vorticity at sea level for the 5-degree "square" within which storm development occurred. The computations are for 1200 GMT, July 22 and 23. A considerable number of ship data existed in the vicinity at both those hours (figs. 1b, d). These data permitted fairly definitive streamline-isotach analyses (not shown), which served as the basis for the computations. Of course no great accuracy can be claimed, but the large convergence at 1200 GMT, July 23, is significant, and it seems realistic in view of the cyclogenesis that was then occurring. From continuity considerations, it is also consistent with the indicated divergence aloft.

There is evidence that similar motions in lesser degree existed in the disturbed area on July 22. The surface depression (figs. 1a, b), the moderately difluent upper-level flow (figs. 2a, b), and the cloud mass (fig. 3) together strongly suggest that an organized pattern of high-level divergence, low-level convergence, and middle-level upward motion was present in the region of the disturbance during July 22 and probably earlier. This pre-existing pattern was itself undoubtedly a factor favorable for cyclonic development and was probably a necessary but not sufficient condition. The arrival of high-level vorticity advection from outside the area thus augmented a pre-existing vertical motion-divergence pattern which had not produced a storm by itself but which provided a favorable "breeding ground" for storm formation. Generally, the importance of the pre-existing disturbance for subsequent tropical storm development is well known and has been discussed by Dunn and Miller [6], Riehl [7], and others.

An invasion of cooler air into portions of the developing circulation is characteristic of extratropical cyclogenesis.

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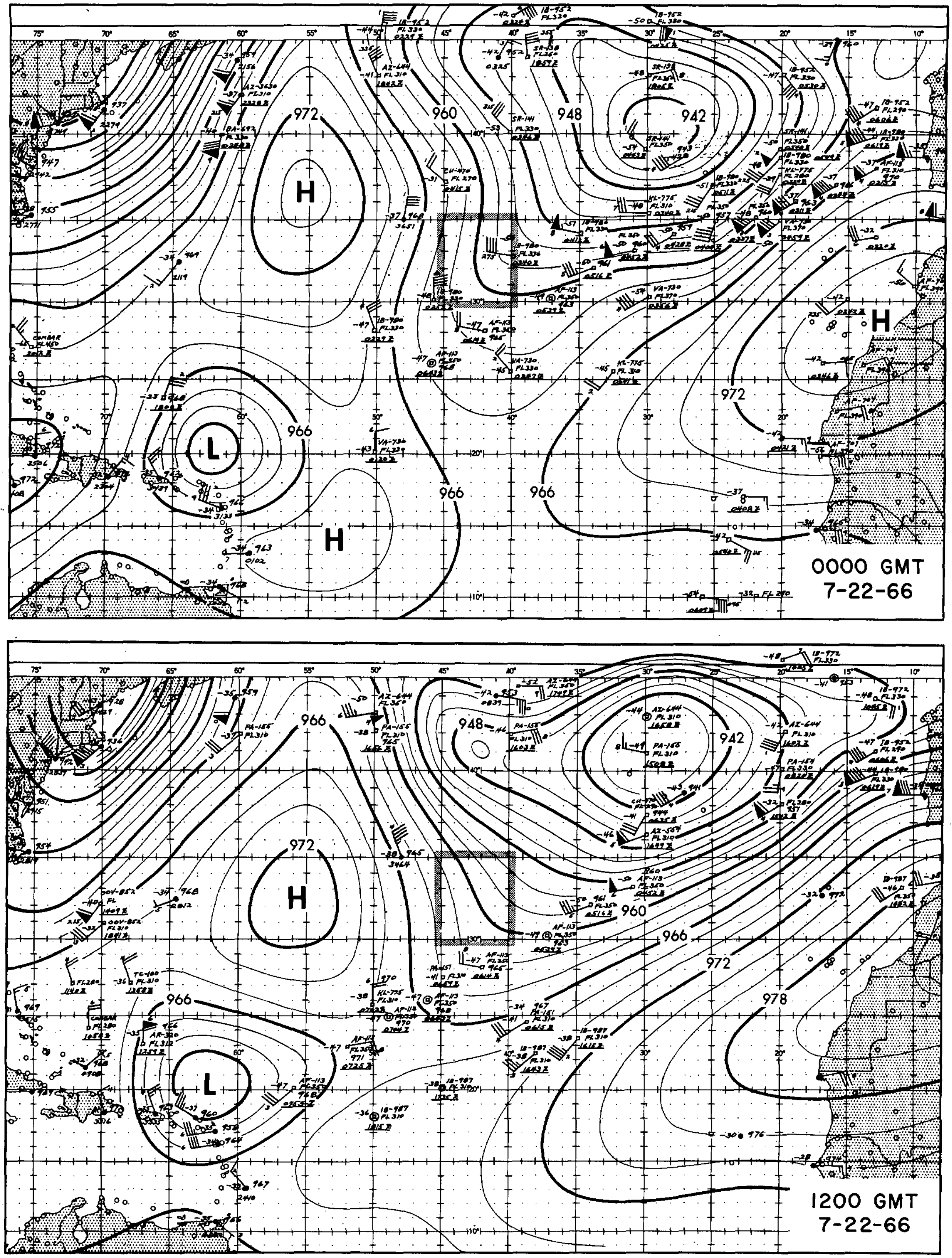
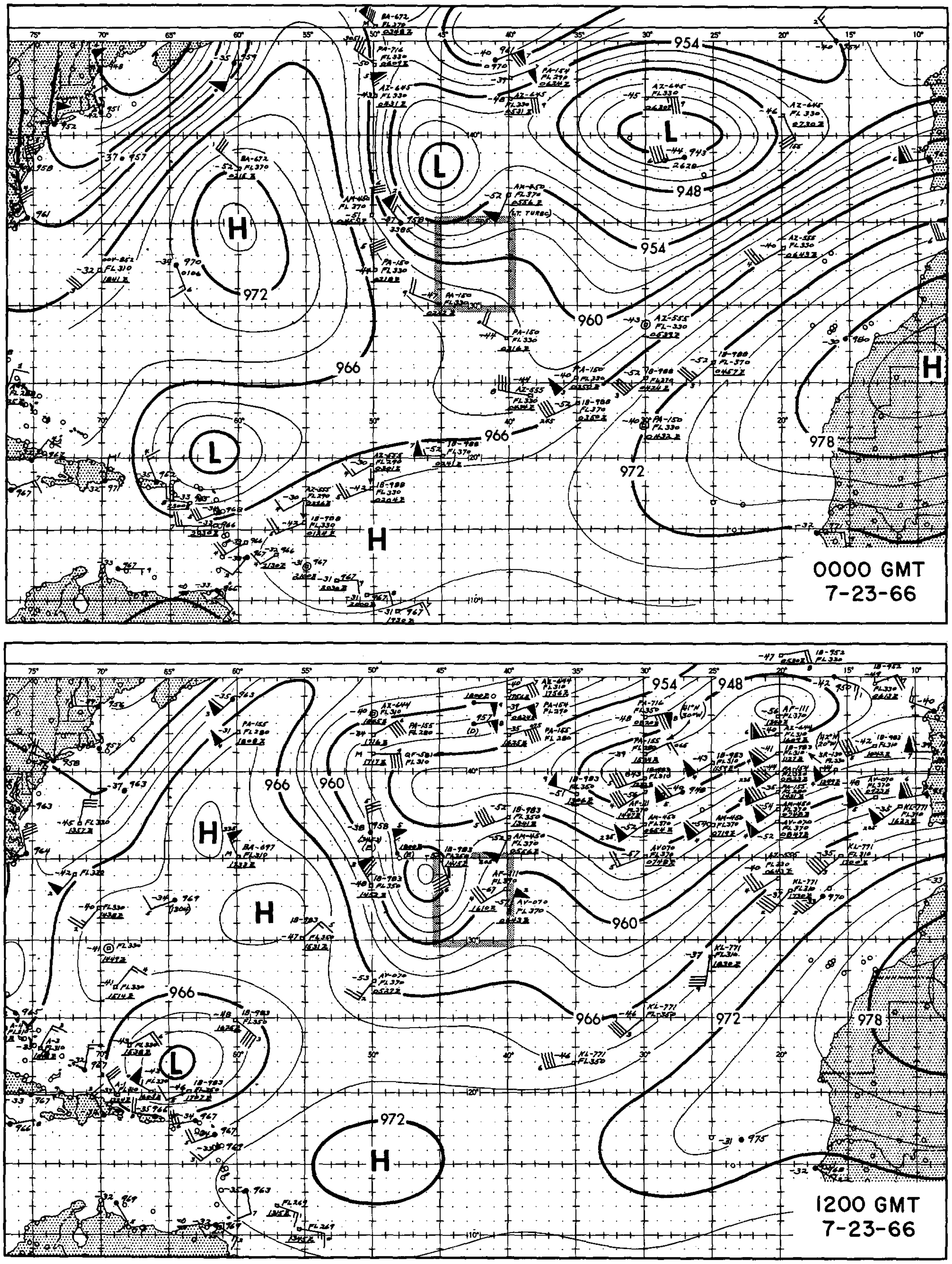
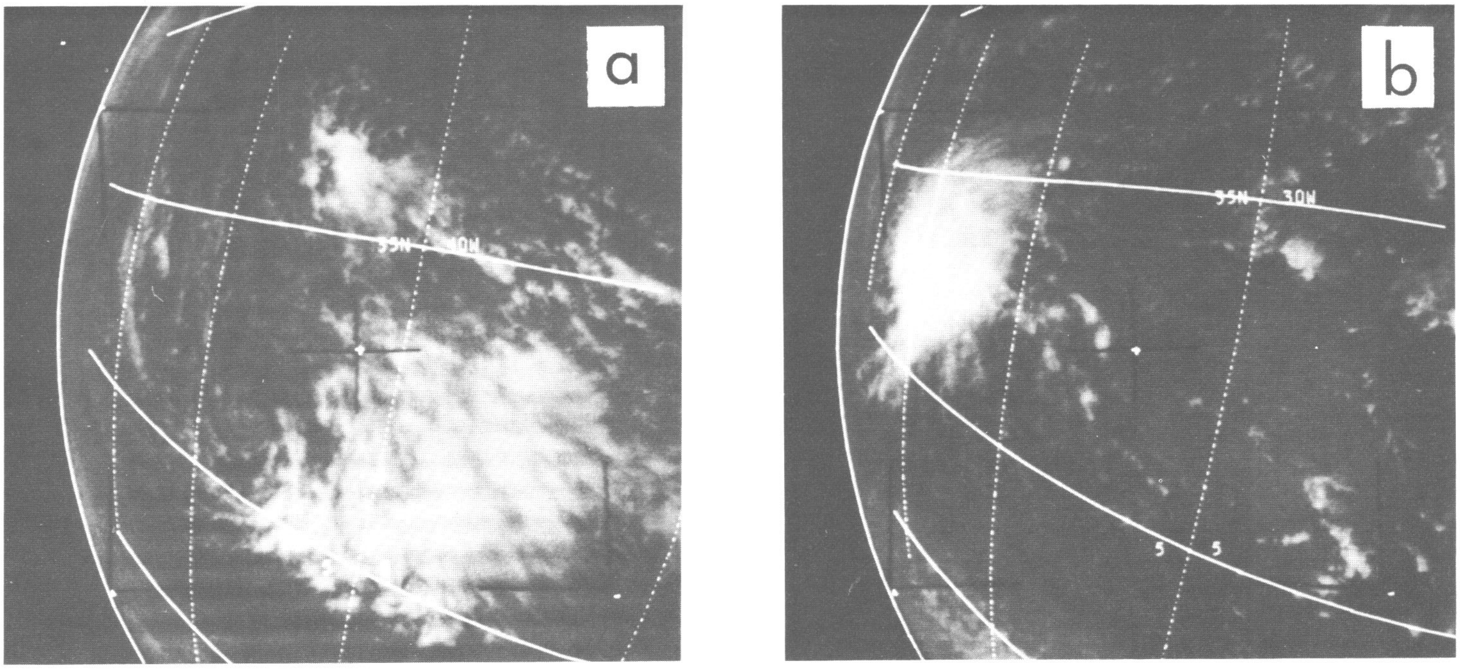


FIGURE 2.—300-mb. analyses: contours are labeled in 10's of gp.m.; contour interval 20 gp.m. Plotted aircraft data are from levels between 27,000 and 39,000 ft. within 6½ hr. of map time. The 5-degree "square", 30°–35° N., 40°–45° W., within which low-level



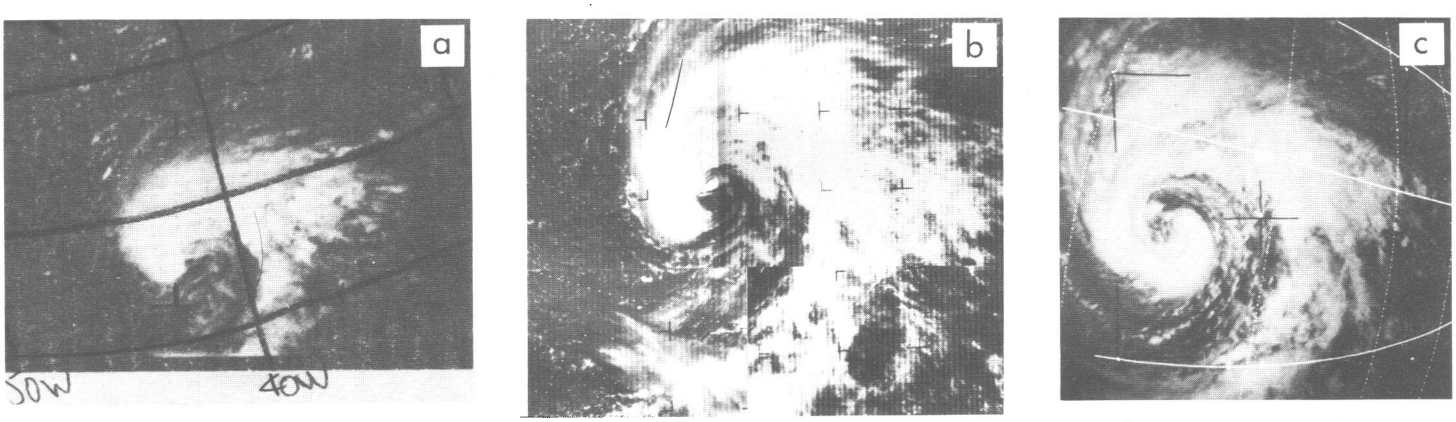
cyclogenesis occurred is outlined by shading. (a) 0000 GMT, July 22; (b) 1200 GMT, July 22; (c) 0000 GMT, July 23; (d) 1200 GMT, July 23, 1966.



July 21, 1537 GMT

July 22, 1501 GMT

FIGURE 3.—ESSA-1 photographs of disturbance on July 21 and 22, 1966. (a) Pass 2415, camera 2, frame 4, 1537 GMT; (b) Pass 2429' camera 2, frame 8, 1501 GMT. Grid interval is 5 degrees.



July 23, 1139 GMT

July 23, 1330 GMT

July 23, 1606 GMT

FIGURE 4.—Three views of developing storm on July 23, 1966. (a) ESSA-2 APT, Pass 1838, 1139 GMT; (b) Nimbus-2 AVCS (composite of four photos), Pass 922, approximately 1330 GMT; (c) ESSA-1, Pass 2444, camera 1, frame 4, 1606 GMT.

The development of a warm core, on the other hand, is a feature of intense tropical cyclones. In the case of Dorothy, the evidence indicates that both occurred. However, neither the cold air invasion nor the warm core was present to the degree that usually exists singly in vigorous extratropical and tropical storms, respectively.

That cooler air did at least reach an area northwest of Dorothy is seen in figure 5, a time-section of the upper-air and surface observations at Weather Ship "E", some 400 mi. northwest of the storm, for the period immediately preceding and during storm development. Pronounced midtropospheric cooling, stratospheric warming, and a general lowering of the tropopause had occurred by July 23, the day of storm formation. On July 24 maximum deviations of $-7°$ and $+13°$ C. were observed (at 450 and 150 mb., respectively). This large midtropospheric cooling in the area northwest of the surface cyclone together with the general northerly flow over that area indicates that the cooler air must have invaded at least the outer portions of the storm circulation. A

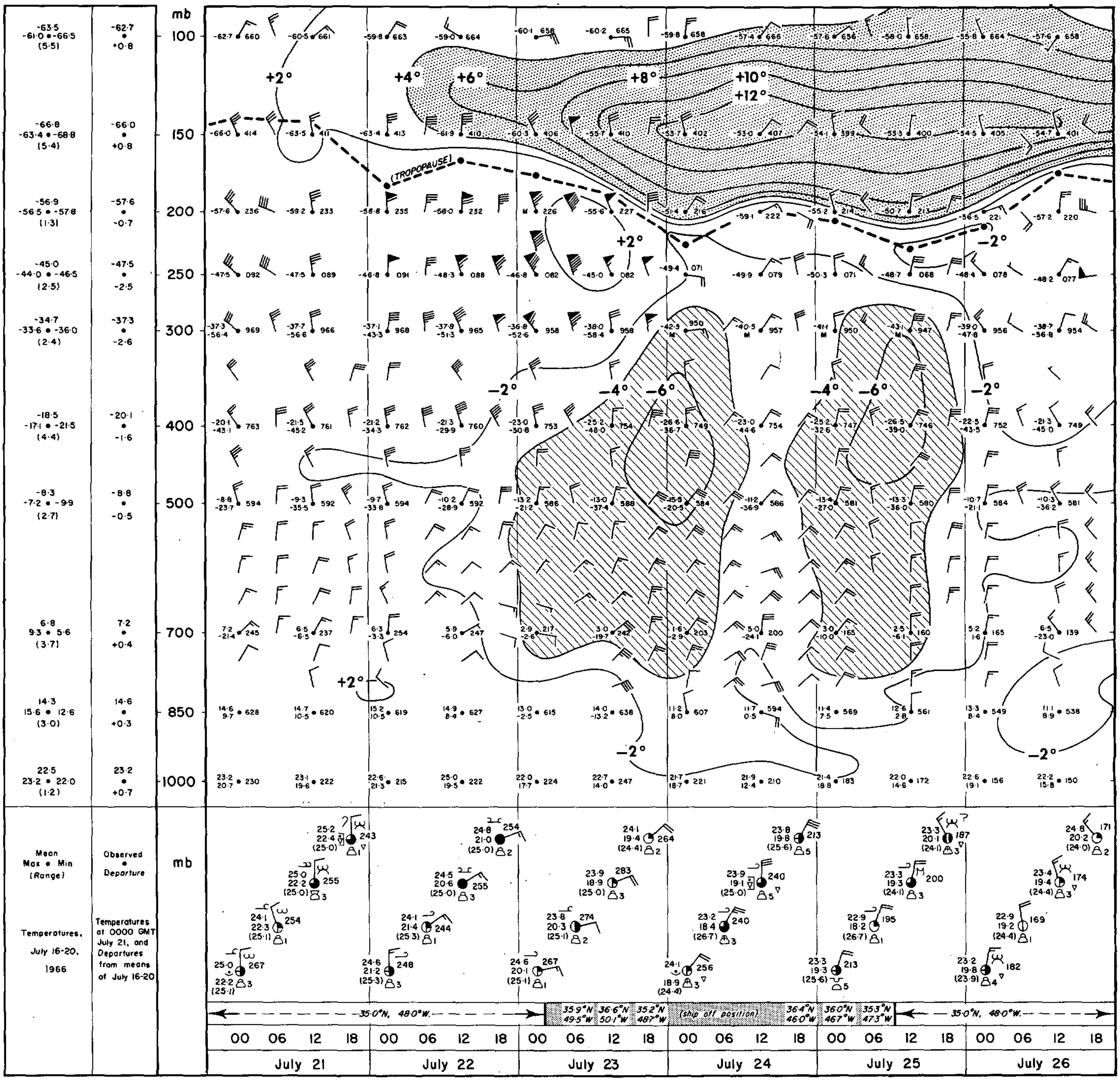


FIGURE 5.—Vertical time-section for Weather Ship "E" (approximate position 35.0° N., 48.0° W.), July 21–26, 1966. Isolines enclose areas of temperature deviations greater than 2° C. from observed values at beginning of period (0000 GMT, July 21). Areas of deviations greater than 4° C. are shaded. Comparative temperature data for the previous 5-day period are shown at left. Surface data are plotted in the standard synoptic code except for sea, air, and dew-point temperatures, which are given to tenths of degrees Celsius.

considerable penetration appears likely, but it is not known whether any such penetration actually reached the storm center.

At the surface at Weather Ship "E", changes were small compared to those that occurred aloft. No clearly defined frontal zone passed that location during the period. However, even at the surface a slight but definite trend toward cooler and dryer air was observed during July 22–24 (see fig. 6).

Thickness analyses, 1000–300 mb., for July 22–23 in the region of the developing storm are presented in figure 7. These are based on the analyses of figures 1 and 2.

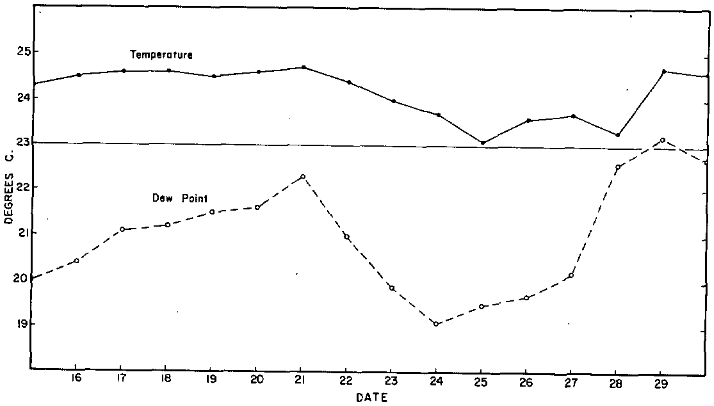


FIGURE 6.—Surface air temperatures and dew points for Weather Ship "E" July 15–30, 1966. Individual values are daily averages of the eight 3-hourly synoptic observations, 0000–2100 GMT.

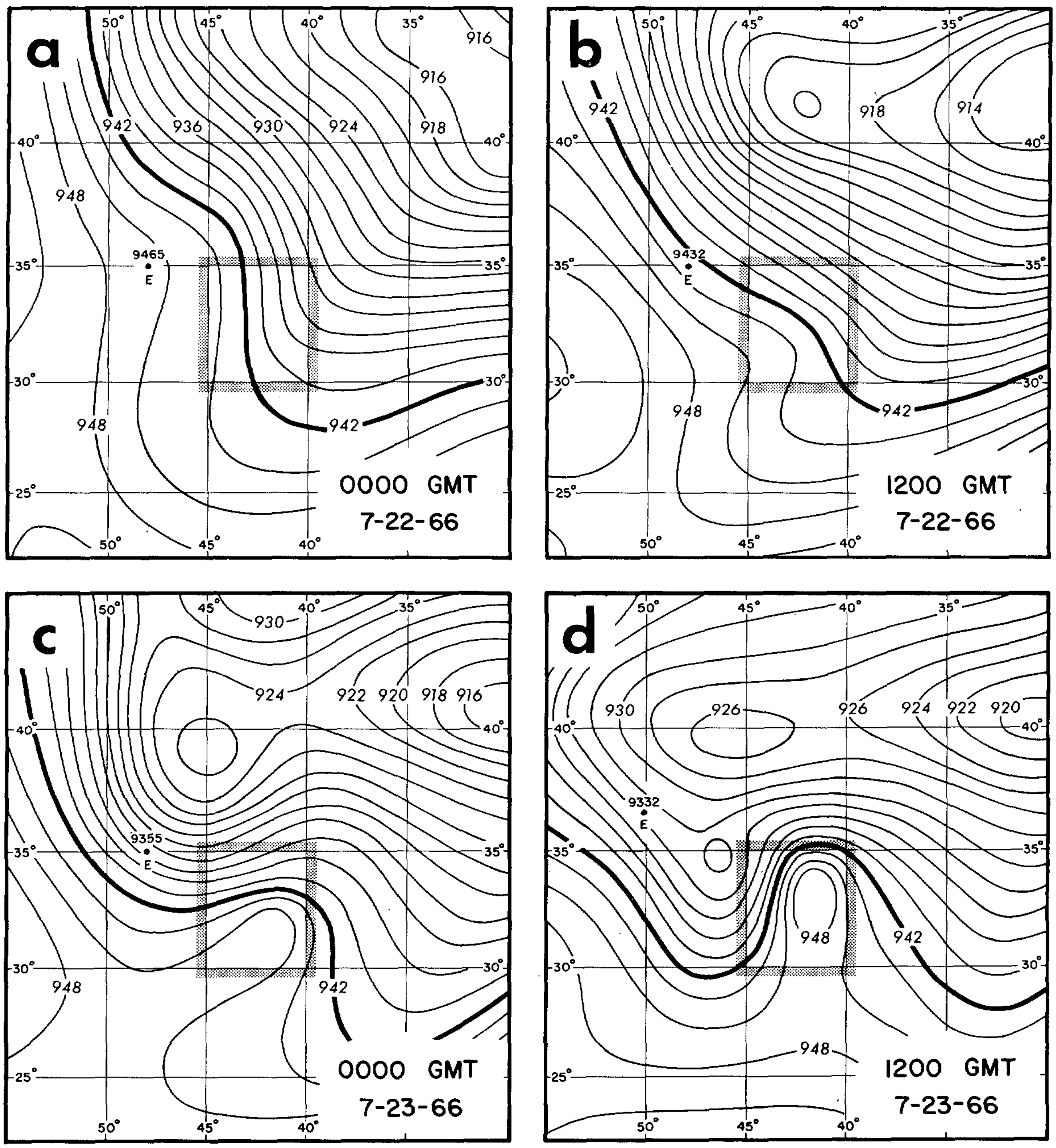


FIGURE 7.—1000–300-mb. thickness contours in vicinity of developing storm Dorothy for (a) 0000 GMT, July 22; (b) 1200 GMT, July 22; (c) 0000 GMT, July 23; (d) 1200 GMT, July 23, 1966. Contours labeled in 10's of gp.m.; contour interval 20 gp.m. Analyses are based essentially on the surface and 300-mb. charts for the same hours (figs. 1 and 2). The 5-degree "square" within which storm development occurred is outlined by shading.

The contour interval of 20 gp.m. corresponds to a difference in mean virtual temperature for the air column of 0.6° C. It is interesting that a moderate gradient of mean temperature already existed at 0000 GMT, July 22, before cyclogenesis occurred. At that time colder air lay to the northeast of the incipient storm and warmer air to the west. As development progressed, warming spread toward the area of the surface cyclone from the west, southwest, and south, while cooling occurred to the north and northwest in conjunction with the approach of the upper trough over that region. By 1200 GMT, July 23 (fig. 7d), these differential changes had produced a zone of considerable baroclinicity over the area immediately west and northwest of the storm center. While details may be questionable because of analysis uncertainties, the gross pattern seems well established. The progressive invasion of the clear tongue spiraling inward from the west and southwest in the satellite photos of figure 4 is corroborative evidence that dryer and probably cooler air was being drawn into the circulation from those quadrants. The photos suggest that some of the dryer air may have penetrated to the storm center on July 23. However, the later formation of an eye (and therefore at least a weak warm core) on July 25–26 indicates that if any such penetration continued, the air must have become so modified as to have differed little from that originally present.

Altogether, it seems likely that the invasion of cooler air contributed to storm development by augmenting convection through large-scale forced uplift of warmer unstable air. Some contribution to cyclogenesis may also have been realized through conversion of potential to kinetic energy. At the same time, the invasion of the dryer, cooler air on July 23 may have interfered with the development of the warm core.

Figure 8 shows that the static stability and the vertical temperature distribution at Weather Ship "E" at 0000

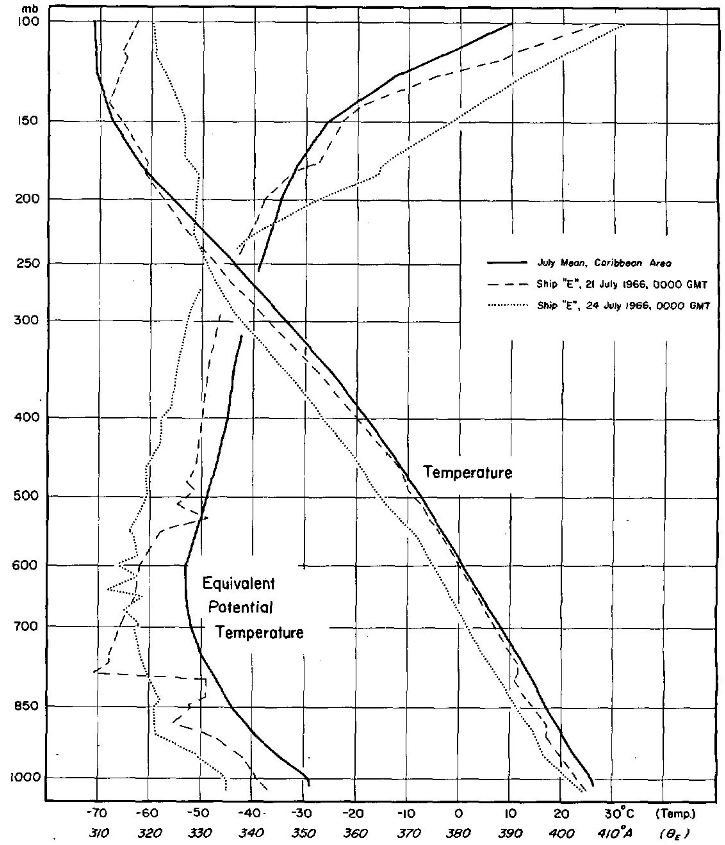


FIGURE 8.—Soundings of temperature and equivalent potential temperature (θ_e) for Weather Ship "E" at 0000 GMT, July 21 (dashed lines) and 0000 GMT, July 24 (dotted lines), 1966. Mean July values for the Caribbean area also are shown (heavy solid lines), based on data published by Jordan [8].

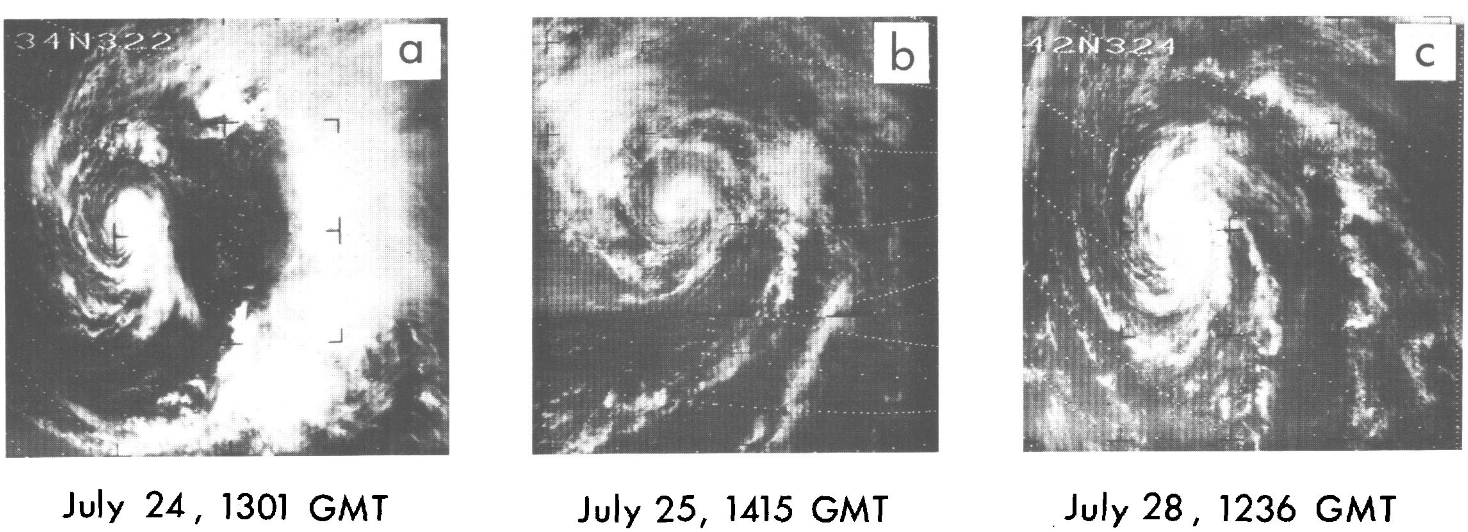


FIGURE 9.—Nimbus-2 AVCS photographs of Dorothy on July 24, 25, and 28, 1966. (a) Pass 935, camera 1, 1301 GMT; (b) Pass 949, camera 3, 1415 GMT; (c) Pass 988, camera 1, 1236 GMT.

GMT, July 21, were comparable to those of the mean Caribbean atmosphere for July [8]. Tropospheric temperatures were only 1° to 3° C. lower than those of the mean Caribbean atmosphere, with lapse rates very slightly greater than the moist adiabatic in both cases. The upward decrease in equivalent potential temperature in the lower troposphere, a measure of convective instability for lifted layers, was in fact larger at 0000 GMT, July 21, than it is for the mean Caribbean atmosphere, although in the latter the instability exists through a deeper layer.

Sea-surface temperatures in the vicinity of the disturbance on July 21–22 were mostly in the range 25°–26° C. This is slightly cooler water than normally observed near incipient hurricanes but is consistent with the slightly cooler air aloft. Thus, conditions favorable for upward transport of heat and moisture—factors necessary for tropical cyclone development—were also present in this situation, but the latent instability did not extend as far aloft as is usually observed in the vicinity of tropical cyclones.

5. LATER EVENTS

Three later views of Dorothy are seen in figure 9. On July 24 (fig. 9a), the major cloud band had become almost completely separated from the smaller area of the storm itself, as the latter remained almost stationary while the former continued to move eastward in advance of the weakening upper trough. A general cyclonic flow pattern aloft remained over and west of the storm area on July 24, but a small and weak warm core may have existed at the center or may have been developing. On July 25 (fig. 9b), an eye was visible. On July 28 (fig. 9c), the general appearance was typical of many tropical storms as seen in satellite photographs.

ACKNOWLEDGMENTS

This work was initiated while the author was on temporary assignment to the National Hurricane Center, Coral Gables, Fla., and was made possible only through the kind cooperation of a number of persons at that office. Some of the ideas developed were obtained through helpful discussions with forecast personnel, in particular Messrs. Neil Frank, Gilbert Clark, and David Shideler of the Miami Weather Bureau.

Thanks also are expressed to Mr. L. F. Hubert, who reviewed the manuscript and made several suggestions for improvement.

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[*Received December 20, 1966; revised January 23, 1967*]